MINISTRY OF EDUCATION AND TRAINING
MINISTRY OF AGRICULTURE AND RURAL DEVELOPMENT

VIETNAM ACADEMY FOR WATER RESOURCES
SOUTHERN INSTITUTE OF WATER RESOURCES RESEARCH

DO DAC HAI

TO STUDY THE MECHANISM OF SALINE INTRUSION AND SUGGEST SOME SOLUTIONS OF SUITABLE WATER EXPLOITATION FOR COASTAL ESTUARY AREA IN THE MEKONG DELTA

Major: Water Resources Engineering

Code: 9 58 02 12

SUMMARY OF PH.D. DISSERTATION

Ho Chi Minh City - 2022

The study is completed in:

Southern Institute of Water Resources Research

Supervisors:

1. Supervisors No.1: Assoc. Prof. Dr. Huynh Thanh Son
2. Supervisors No.2: Prof. Dr. Nguyen An Nien

Reviewer No. 1: ……………………………………………........................

Reviewer No. 2: ……………………………………………........................

Reviewer No. 3: ……………………………………………........................

The Dissertation will be defended in front of the Evaluation Council of the Vietnam Academy for Water Resources.

Meeting at Southern Institute of Resources Research

Address No. 658 Vo Van Kiet, Ward 1, District 5, Ho Chi Minh City.

At...............in............2022

The thesis is available at:

- National library of Vietnam.
- Library of Vietnam Academy for Water Resources.
- Library of Southern Institute of Water Resources Research.

INTRODUCTION

1. Necessity of thesis topic

The Mekong Delta has an important position in socio-economic development with great potential for agriculture and fisheries, recently, the Mekong Delta has always contributed about 53% of the total food output. 65% of aquaculture production and 70% of fruits of the whole country. From 2005 till now, the Mekong Delta has always reached over 19 million tons of paddy and the annual export volume is from 4-5 million tons. The Mekong Delta is located in the lower part of the Mekong River, with low-lying topography, so it is always influenced by tides and saline intrusion from the East and West Sea. Saline intrusion causes very serious consequences, affecting daily life and production of the whole Mekong Delta. In particular, in 2016 and 2020, saline intrusion into the Mekong Delta had a great impact and caused serious consequences, which was evaluated the most in the past 100 years. Salinity tends to come earlier, right from February, the salinity has remained high and severe. On Tien and Hau rivers, the salinity is over 4.0‰, intruding further up to 70 km from the estuary, even up to 85 km in some places.

To exploit, develop and learn about the natural features of the Mekong Delta, up to now, there have many studies on salinity for coastal estuaries. The studies were carried out quite early after the unification of the country, from simple initial studies by monitoring and sampling to in-depth studies with more modern research equipment and methods. The studies have been applied to actual production in planning, production zoning, design and construction of hydraulic and saline control works,. Research on saline intrusion is done quite a lot and often, however, in-depth studies on the mechanism of saline intrusion, disturbance or stratification for the coastal estuaries of the Mekong Delta are still very limited.

With the aim of contributing, enriching and further perfecting the studies on salinity for coastal estuaries in the Mekong Delta, in this study, the PhD student has focused on in-depth research on the mechanism of saline intrusion, the formation of saline stratification (salt wedge) at the estuaries of the Mekong River. The research results have evaluated the characteristics of the saline intrusion mechanism more complete than existing studies and applied more effectively in production practice. From the research results, a number of reasonable water exploitation solutions have been proposed for the coastal estuaries of the Mekong Delta. At the same time, with the results of this research and further research development will be the premise to come up with solutions to limit saline intrusion for the present as well as in the future when considering sea water rise factor by solutions projects such as barrage to control saline, subsurface dams to prevent saline, salt traps, works to collect water for agriculture and fisheries … and non-structural solutions such as operating a system of saline control gates and to take fresh water upstream for agriculture or to take deep saltwater for aquaculture growing... At the same time, the research results of the topic can support relevant studies on the environment, ecology, alluvial deposition, accretion... in coastal estuaries.

2. Study objectives

- To define the mechanism of saline intrusion, the formation of saline stratification, structure, existence and activities of salt wedge of coastal estuary area in the Mekong delta in current situation and sea water rise due to climate change.
- To use the study results in the water resources development, forecast, to increase the water intake based on the requirement of different salinity concentrations according to space (river layout, horizontal, vertical and depth), according to time to take initiative production activities related to water and it is the premise to suggest the suitable solutions of salinity control for the study area.

3. Study subject and scope

Study subject: Coastal estuaries have been intruded by saline water.

Study scope: Estuaries of Mekong River and it is focused in detail on Hau estuary (02 branches Dinh An and Tran De).

4. Approaches and methodology

Approaches: The thesis chooses an integrated approach including: (1) Integrated approach; (2) Practical approach; (3) Access to information integration; (4) Access to advanced technologies; (5) Approach to inherit and develop research results.

Research methods: (1) Inheritance method; (2) Methods of integrate and collection; (3) Field survey method; (4) Analytical method; (5) Mathematical modeling methods, application of scientific advances; (6) Method of comparison of practical relations..

5. Scientific and practical significance of the thesis

Scientific significance: The study results have the significance to clarify more the saline intrusion mechanism, variation of stratification, salt wedge based on space and time at the coastal estuary area of the Mekong River system. The study has been applied the 3 D model (MIKE 3) to simulate the saline intrusion process at the estuary area, the model has been calibrated and verified with observed data, a set of model parameters is a basis for the following study.

Practical significance: The study has been applied the 3 D model (MIKE 3) to simulate the saline intrusion process at the estuary area, the model has been calibrated and verified with observed data, a set of model parameters is a basis for the following study. The results have also given the water intake ability based on the requirement of different salinity concentration according to space (river layout, horizontal, vertical and depth), according to time to take initiative the different water usage requirement. In addition, the study has been oriented the basis to propose suitable water development solution for coastal estuary area of the Mekong delta (design idea, upgrade, the adjusted way of work operation method based on the requirement of salinity concentration suitable to the different production needs at the estuaries of the Mekong Delta)…

6. New contribution of the thesis

- Some empirical parameters can be used to preliminarily evaluate the stratification phenomenon for the 7 branches of the Mekong River in space (along the river) and in time.
- Set up a 3 D model (MIKE 3) and simulate the characteristics of saline intrusion, saline distribution, structure (shape, size, slope), formation, existence and development of salt wedge at two branches of Hau river.
- Based on the results of the simulation of saline intrusion, the saline stratification, it has oriented the basis for proposing a reasonable water development solution for the coastal estuaries of the Mekong Delta (design ideas, upgrading, direction of adjustment the way how to operate the works according to the requirements of salinity concentration in accordance with different production requirements in the estuary of the Mekong Delta).

CHƯƠNG 1. CHAPTER 1. OVERVIEW OF STUDY ISSUES

1.1. Overview of saline intrusion in the Mekong Delta

The Mekong Delta has two sides bordering the East Sea and the West Sea with a coastline of more than 700 km with flat topography, most of the altitude is lower than the peak tide water level, so it is affected by tides and saline intrusion, especially in the dry season. The natural area of the Mekong Delta is about 4 million ha; in which the area that is likely to be affected by flooding and saline intrusion is about 2 million ha, fluctuating annually depending on the water source comes to the delta.

The source of saline intrusion from the sea through the main estuaries goes further into the infield canals in the provinces of Tien Giang, Ben Tre, Tra Vinh, Soc Trang, Bac Lieu and Ca Mau. The Tien River, the section from Vinh Long - My Tho, in turn forms successive large estuaries, namely Co Chien, Ham Luong, Ba Lai, Cua Dai, and Cua Tieu. The Ba Lai stream was formerly a small estuary of the Mekong River, since 2001, the Ba Lai dam had been built. Hau River flows in a straight line and is about 30 km far from the sea, then seperates into 2 streams that come into the sea through Dinh An and Tran De estuaries. The length of saline intrusion into the main river in years is almost unchanged, the difference between years is about 2-5 km, except for special dry cases such as in 2016 and 2020.

1.2. Overview of international studies

1.2.1. Definition of estuary area

There are many studies on the definition of eastuary area by authors such as Ritter K, Posen O. (1866), Lapparent, A. (1907) and Haug, E. (1911), Sukin C. (1938), Nhikolaev N. I. (1949)), Khain E. (1973). Currently, Pritchard's definition of Estuary is the most notice. Accordingly, “Estuary is a semi-enclosed coastal water body connected to the open sea, in which there is a certain mixture of saltwater and fresh water flowing from the continent” and Pritchard, Leeder divided estuaries into 4 types based on salinity balance that shows the stratification and accretion ability: Type A: strong stratification, dominant riverbed process, strong accretion; Type B: partial disturbance, inclined to accretion is the common type; Type C: vertical uniformity in cross section, strong tidal current and no bottom accretion; Type D: uniform in the vertical direction and along the flow, the material movement is completely dominated by the tidal current and strongly eroded by the flow.

Classification of estuaries by flow regime (salty, freshwater interactions): To understand the exchange and circulation of coastal estuaries, Pritchard (1955), Cameron and Pritchard (1963) classified estuaries on the basis of flow stratification and salinity distribution. According to stratification criteria, there are: Highly stratified estuaries; Partially mixed estuaries; Estuaries are well-mixed or homogenous.

1.2.2. Characteristics of stratified estuary (salt wedge)

When fresh water flowing from the mainland into an estuary is dominant and tidal current is weak, a marked difference in salinity will be formed between the upper and deeper layers. In fact, part of the friction at the interface causes it to tilt downward towards the upstream, thus forming a wedge-shaped saline intrusion.

One characteristic of the salt wedge system is gradient, the large density gradient at the interface is strongly suppressed the vertical turbulence component, thus reducing the disturbance across the interface to a minimum level. The characteristics of stratified estuaries are studied according to the movement at high tide in stratified estuaries (salt wedges) and movements at low tide in stratified estuaries. Studies on the separations at stratified estuaries including: Interfaces created by warming water surface; The interfaces are created by the salt heat gradient; scattered interfaces; sliding interfaces;

1.2.3. Research involving partially stratified estuaries

Observations in partially stratified estuaries have shown that velocity and density structures can undergo significant changes during a tidal cycle, leading to marked changes of the effective vertical dispersion K_{xe}. Analysis of the up and down movements of stratified estuaries fully shows that significant and sometimes rapid changes in density and velocity structures can occur in salt wedge estuaries. These are called strong disturbance cycles (IMP), which are observed in partially stratified systems.

1.2.4. Some typical computational studies on saline intrusion

Research on the mechanism of saline propagation and salt wedges in coastal estuaries has been studied for a long time in the world and pioneered by US scientists who have studied from theory and applied it to practice. Since the early 1950s, studies on salt wedges have been studied by the following authors: Harlow G. Farmer (1951) experimental research on salt wedges; Harlow G. Farmer and George W. Morgan (1953) had analytical solutions for salt wedges. Along with the development of the calculation method, the salt wedge problems have been studied and solved by numerical methods with large mathematical and physical models. Studies by C. Ibaneza, J. Saldana and N. Prat (1999) of Spain are carried out for salt wedge of the Ebre estuary on the basis of Keulegan's research on the stopping mechanism of salt wedges. The authors Geyer, W. R, Smith, J. D, Farmer, D. M Geyer (1985) focused on the study of the active time of salt wedges.

1.3. Research situation in Vietnam

The number of studies on saline intrusion in the estuary in general and the Mekong Delta is quite large by specialized organizations such as the Southern Institute of Water Resources Research, the Southern Institute of Water Resources Planning; Water Resources University... and prominent scientists such as Prof. Dr. Nguyen An Nien, Prof. Dr. Le Sam, Prof. Dr. Nguyen Tat Dac, Prof. Dr. Tang Duc Thang, Assoc. Prof. Dr. Nguyen Nghia Hung, Dr. Luong Quang Xo, Prof. Dr. Nguyen Quang Kim, Dr. Nguyen Anh Duc... The current studies on salinity calculation are mainly carried out by field survey combined with one-dimensional (1D) hydraulic model. Research using basic 1D model has met the requirements for production, but has not shown the nature of the saline intrusion mechanism. Up to now, there are only some stratified saline intrusion calculations that are carried out by Prof. Dr. Nguyen Quang Kim for the Dong Nai estuary and by Prof. Dr. Nguyen Tung Phong calculating for the Ninh Co and Day rivers.

The measurements of stratified salinity in the estuary of the Mekong Delta are also quite limited, typically some of measurements were carried out by the Southern Institute of Water Resources Planning in a JICA-funded project during the period 2011-2013; Dr. Nguyen Anh Duc in 2008 and the research team of Assoc. Prof. Dr. Nguyen Nghia Hung in 2016.

CHƯƠNG 2. CHAPTER 2. OVERVIEW OF THEORY AND TOOLS IN THE RESEARCH ON THE MECHANISM OF SALINE INTRUSION IN THE COASTAL ESTUARIES

2.1. General structure of salt wedge in the estuary

The two-layer theoretical principle applied to develop a predictive model of the saline intrusion length of a salt wedge was one of the earliest attempts to describe the exsistent mechanism of one salt wedge that is developed by Schijf et al. Schonfeld in 1953. The hypothesis of a system consisting of two homogeneous layers of fluid (salt water and fresh water) that are separated by a distint interface is considered. The density difference between the two fluids is assumed to be small compared to the density itself: $\varepsilon = (\rho_2 - \rho_1): \rho_2 \approx (\rho_2 + \rho_1)/2 \approx \rho 1$.

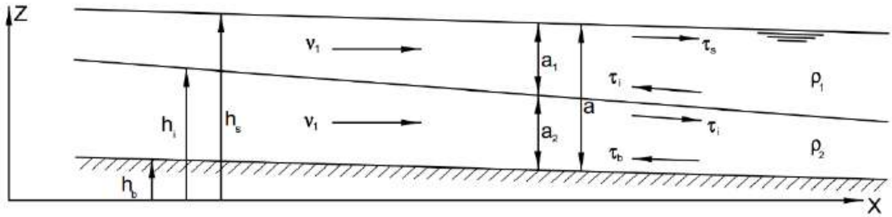


Figure 2-1: Two-layer system, based on Schijf and Schönfeld (1953)

Ignoring the longitudinal acceleration components, the dynamic and continuity equations can be written as:

$$\frac{\partial a_1}{\partial t} + v_1 \frac{\partial a_1}{\partial x} + a_1 \frac{\partial v_1}{\partial x} = 0 \qquad (2\text{-}1)$$

$$\frac{\partial a_2}{\partial t} + v_2 \frac{\partial a_2}{\partial x} + a_2 \frac{\partial v_2}{\partial x} = 0 \qquad (2\text{-}2)$$

$$\frac{\partial v_1}{\partial t} + g \frac{\partial a_1}{\partial x} + g \frac{\partial a_2}{\partial x} + v_1 \frac{\partial v_1}{\partial x} + g(i_1 - i_b) = 0 \qquad (2\text{-}3)$$

$$\frac{\partial v_2}{\partial t} + (1-\epsilon) g \frac{\partial a_1}{\partial x} + g \frac{\partial a_2}{\partial x} + v_2 \frac{\partial v_2}{\partial x} + g(i_2 - i_b) = 0 \qquad (2\text{-}4)$$

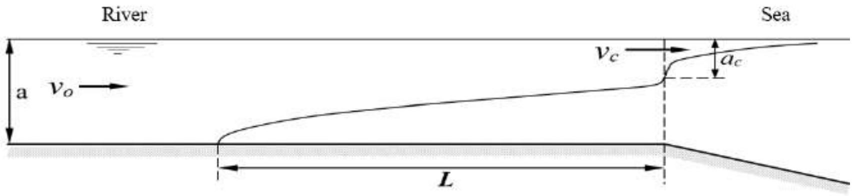


Figure 2-2: Salt wedge shape is developped by Schijf và Schonfeld

The upper layer flow is mainly decisive at the estuary, so an equation describing the interface can be obtained by combining the momentum equations of the two layers.

$$\epsilon g \frac{da_1}{dx} + v_1 \frac{dv_1}{dx} + \frac{v_1^2 a}{4C_i^2 a_1 (a - a_1)} = 0 \qquad (2\text{-}5)$$

Where: C_i is the coefficient of friction along the interface, ϵ is the density difference between the two layers, a is the depth of the upstream freshwater layer, and v is the flow velocity upstream of the river.

The integration of equations of interfaces is rewritten as follows:

$$L = \frac{C_i^2}{g} a \left[\frac{1}{5} \frac{\epsilon g a}{v_0^2} - 2 + 3 \sqrt[3]{\frac{v_0^2}{\epsilon g a}} - \frac{6}{5} \sqrt[3]{\frac{v_0^2}{\epsilon g a}}^{2} \right] \qquad (2\text{-}6)$$

Where: v_0: the increase in upper layer thickness in the estuary, $a_c = \frac{v_0^2}{\epsilon g}$ the increase in friction between the interface and the slope. Therefore, the length of the salt wedge is reduced by the above reasons. When the river flow velocity v_o becomes much larger than the double velocity, v_{cc}, the salt wedge is completely extruded out of the river estuary.

Keulegan also developed the relationship for the existing length of the salt wedge (Keulegan 1966). If ρ is the density of fresh water; $\rho + \Delta$: density of seawater and ρ_m being the density of two fluids, Keulegan noted that the deposited velocity can be determined by:

$$V_\Delta = \sqrt{\frac{\Delta\rho}{\rho_m} g H} \qquad (2\text{-}7)$$

Where: g is the acceleration due to gravity and H is the depth of the river.

In a similar flow, the density Reynolds number is determined by:

$$R_e = V_\Delta \frac{H}{\nu} \qquad (2\text{-}8)$$

where ν is the kinematic viscosity of water. Note that the surface slope of the water in the river plays only a secondary role in the existence of the salt wedge, to predict the relationship between the velocity of the saltwater interface V and the displacement distance, L has formed:

$$\frac{V}{V_\Delta} = f_0\left(\frac{L}{H}, \frac{V_r}{V_\Delta}, \frac{V_\Delta H}{\nu}, \frac{H}{B}\right) \quad (2\text{-}9)$$

Where V_r is the velocity of the river inversely proportional to the increase of the salt wedge. Accordingly, a relationship with the length of a salt wedge exists, L has formed:

$$\frac{L_0}{H} = f\left(\frac{V_r}{V_\Delta}, \frac{V_\Delta H}{\nu}, \frac{H}{B}\right) \quad (2\text{-}10)$$

From the movement data, Keulegan established the following law of length as follows:

$$\frac{L_0}{H} = A\left(\frac{V_r}{V_\Delta}\right)^{-5/2} \quad (2\text{-}11)$$

With a variable A, for a constant river width compared to water depth ratio, Equation (2-10) recommends that the variable A depends on the Densimetric Reynolds number, $V_\Delta H/\nu$. The natural flow of water with a Reynolds number of 10^7 or greater is shown by the relationship:

$$\frac{L_0}{H} = 6.0\left(\frac{V_\Delta H}{\nu}\right)^{1/4}\left(\frac{2V_r}{V_\Delta}\right)^{-5/2} \quad (2\text{-}12)$$

In addition to assuming steady-state conditions, other important hypothetical conditions allow a solution for the salt wedge shape to exist are: low tide, rectangular uniform cross-section with horizontal bottom and constant, undisturbed water depth along the interface and consecutive coefficient of friction along the saltwater and freshwater interface (Harleman, 1990).

With these assumptions in mind, Harleman showed that the theoretical shape of the existing salt wedge could be presented in an unlimited way as a function of Froude number to measure the density, F_0, based on the mean water flow rate U_0 and the depth h_0 upstream of the existing salt wedge as follows:

$$F_0 = \frac{U_0}{\sqrt{g' h_0}} \text{ với } g' = g\frac{\rho_2 - \rho_1}{\rho_2} \quad (2\text{-}13)$$

For the existence of the salt wedge without the entrainment, the average velocity at the bottom is zero. At the junction between the river and the sea, the relative depths of the two layers are such that the local density Froude number of the upper layer is equal to the overall one. Therefore, upper layer flow is essential and the depth ratio at the entrance is:

$$\frac{h_{ic}}{h_0} = (\mathbf{F}_0)^{2/3} \quad (2\text{-}14)$$

Where: when $h_{ic} = h_0$; salt wedge is extruded out of the river and $F_0 = 1$ (Harleman, 1961).

Arita and Jirka extended the two-layer theory by introducing a formula based on the zero velocity line (ZVL) as an alternative to the concentration interface as shown in Figure 2-3. The disturbance and entrainment at the interface were ignored but cyclic dynamics in the lower layer were included (Arita and Jirka, 1987).

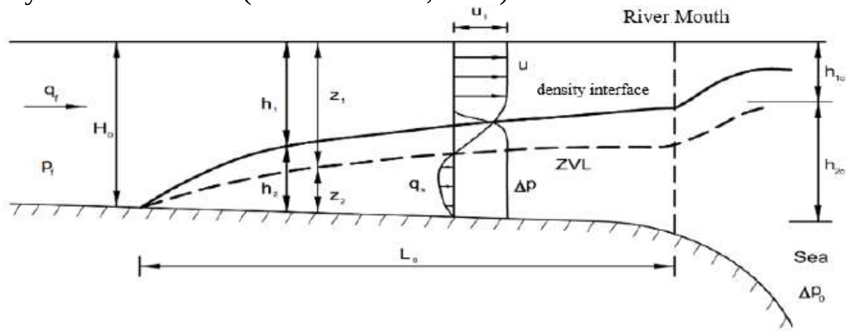


Figure 2-3: Shape and structure inside salt wedge

The two-layer equation was solved by numerical method and predicted the salt wedge length as a function of Reynolds number. Corrected Reynolds number for width ratios, different width is used in different tests by calculating and using the relation document.

2.2. Empirical parameters determining estuary stratification

To determine the flow mechanism in coastal estuaries (estuary classification) is currently divided into 03 types: Completely disturbed - Type I (no stratification or weak stratification); partial disturbance - Type II (medium stratification) and weak disturbance - Type III (strong stratification or formation of salt wedges). In order to classify estuaries according to the above three types, there are a number of methods such as: empirical formulas, observed data, computational models, these methods of analysis and evaluation depend on numerical sources, data…accuracy requirement and calculation aim.

Studies on three types of vertical mixing and water stratification were carried out in the United States by D. Pritchard in the 1950s. The different intrusion conditions of seawater in estuaries are suitable for these vertical mixing and startification. Through the analysis and evaluation in the thesis, Ph D student has used two empirical parameters to determine the stratification ability for the Mekong river estuaries that are: stratification parameter n and tidal flood parameter α. The stratification parameter n is widely used after the studies of D. Pritchard. This parameter is expressed as:

$$n = \frac{\Delta S}{S_m} = \frac{S_{bot} - S_{surf}}{0.5(S_{bot} + S_{surf})} \qquad (2\text{-}15)$$

Where:

ΔS: Salinity concentration difference by vertical direction

S_m: Medium salinity

S_{bot} và S_{surf} Salinity at bottom and surface layers

One parameter also recognized by many studies is that the tidal and flood interaction parameter α characterizes the relationship between the effects of the sea and the changes on the estuary regime. This parameter is named in the document that is whether Canter Cremers number or Simmons parameter. The tidal flood parameter is defined as:

$$\alpha = \frac{W}{P_t} = \frac{Q_m \tau}{P_t} \qquad (2\text{-}16)$$

where:

W: Volume of flow from a river during a tidal cycle (m^3)

Q_m: River flow during low tide period

τ: Low tide time

P_t: Volume of the tidal prism

The P_t value is usually determined by using simple formula $P_t = \Delta H_{tide} F_m$, where ΔH_{tide} is the mean tidel range of entrance (cross section) having the area is F_m.

The formula (2-16) is a fairly complete one taking into account the factors determining the stratification such as topography, hydrology, etc. of the estuary section through the tidal prism factor. However, to determine exactly the tidal prism for the estuary area is a very difficult problem depending on many factors: the limit of the prism, the topography of the entire estuary, the tide influence area (seasonal change and upstream flow), river flow and tidal energy ... therefore, to simplify the Simmons parameter , other different calculation methods were also mentioned by Prof. Dr. Nguyen An Nien studies.

$$\eta = \frac{W^+}{W^-} \qquad (2\text{-}17)$$

Where:

W^+: amount of river flow during low tide cycle (m^3);

$W^+ = \Sigma Q^+ \times \Delta t_x$; Q^+: flow rate at low tide time (m^3/s).

W^-: Amount of reverse flow during high tide phase (m^3);

$W^- = \Sigma Q^- \times \Delta t_l$; Q^-: flow rate at high tide time (m^3/s).

Table 2-1: Some criteria to determine the ability of saline stratification in Estuary

Classification	Characteristic		n	α	η
	Disturbance	Stratification			
I	Completely disturbed	Weak	0÷0,1	0÷0,1	≤0,1
II	Partially disturbed	Average	0,1÷1,0	0,1÷1,0	0,2 - 0,5
III	Weak disturbance yếu	Strong	1,0÷2,0	>1	η ≥ 0,7

2.3. Application of empirical parameters to determine preliminary the stratification mechanism in the Mekong Delta estuary region

In this study, the stratification ability for the Mekong River estuaries is determined according to the formulas and empirical coefficients based on the results of hydraulic calculation (discharge) by using 1D model (coefficient η) and for two branches of Hau river is based on actual data monitoring the salinity according to flow depth (coefficient n).

2.3.1. Calculation for estuaries according to Simmons parameter (η)

The amount of river flow in a tidal cycle (W+) and tidal flow (backflow) during the high tide phase (W-).

The input data (discharge) are calculated based on the average cross-sectional discharge along the river extracted from the results calculation of 1D model MIKE 11 for the whole Mekong Delta of the Southern Institute of Water Resources Research.

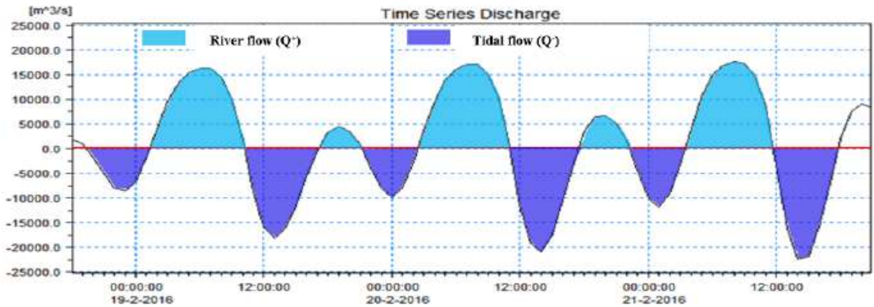


Figure 3-1: Illustration of river flow (Q+) and tidal flow (Q^-)

Calculation for 7 eatuaries including: Cua Tieu, Cua Dai, Ham Luong, Co Chien, Cung Hau (Tien river), Ba Lai tributary is not calculated because Ba Lai sluice is almost closed during the dry season and Dinh An, Tran De (Hau river).

- ❖ Calculation result of coefficient η

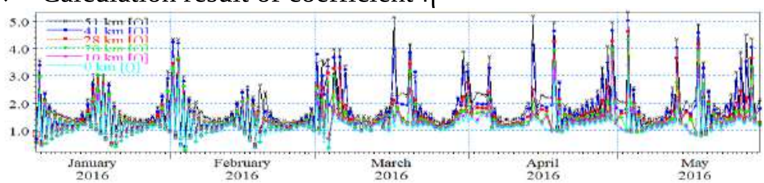


Figure 3-2: Calculation results of coefficient η at some locations on Cua Tieu branch

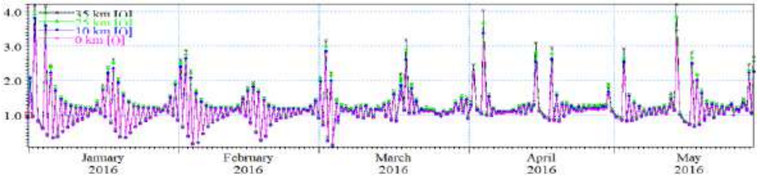


Figure 3-3: Calculation results of coefficient η at some locations on Cua Dai branch

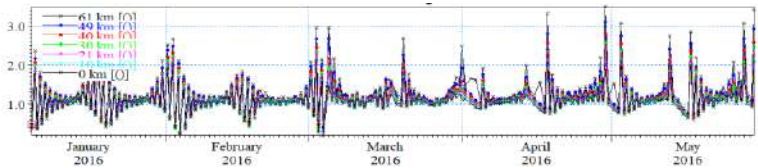


Figure 3-4: Calculation results of coefficient η at some locations on Ham Luong River

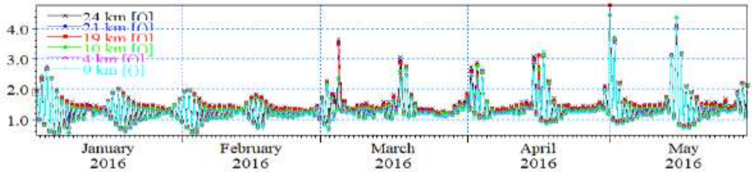


Figure 3-5: Calculation results of coefficient η at some locations on Co Chien river branch

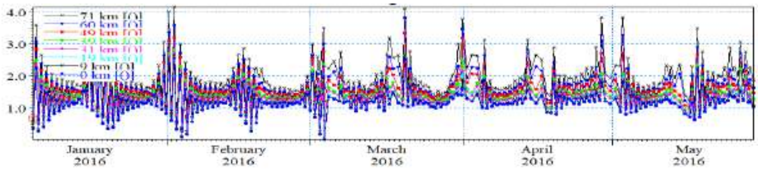


Figure 3-6: Calculation results of coefficient η at some locations on Cung Hau estuary branch

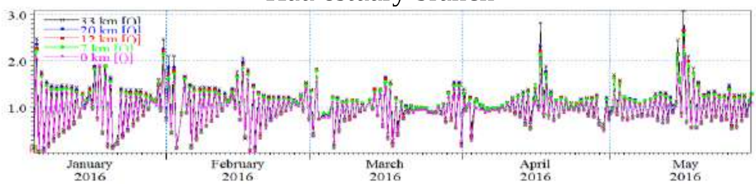


Figure 3-7: Calculation results of coefficient η at some locations along Dinh An estuary branch

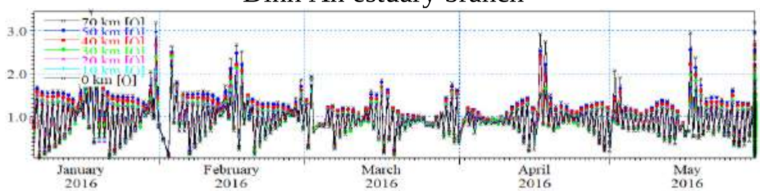


Figure 3-8: Calculation results of coefficient η at some locations along Tran De estuary branch

From the calculation results of parameter η, it is shown that on the Mekong estuaries, there are some main characteristics for all estuaries as follows:

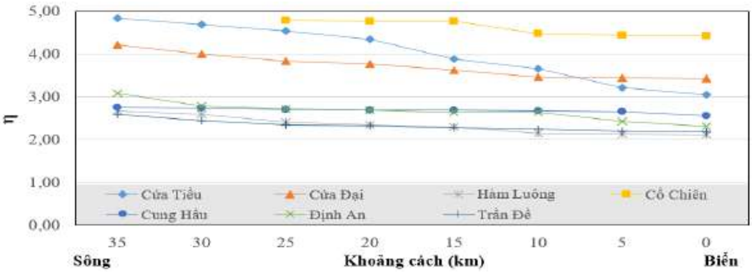
1. The calculation results also show that the value of η depends closely on the tidal cycle and the tides of the day. During the high tide cycle (time from days 8-12, 23-26) the coefficient η is lower than that of the low tide period. In one day there is a significant difference in the coefficient η in high tide and low tide. The time of strong stratification (salt wedge) is when the high tide occurs and especially the low tide period, the coefficient η is higher than other times. In a tidal cycle, the difference in the coefficient η in the tides is also different. When the tide is high, the coefficient η is not much different, but in the low tide the difference is quite large.
2. There is a change of the coefficient η over time during the dry season and there is a difference between the Tien and Hau rivers. To start from about March 8 (Tien river estuaries) and March 15 (Hau river estuaries) at the calculated locations, the trend of η tends to increase more than at the beginning of the dry season. From this result, it can be seen that the river flow (Q+) changes (increases) on the Tien estuaries about 4-7 days earlier than the Hau estuaries.

From the calculation results, it is possible to compare the values of η between the branches on the Tien River and the Hau River or compare all 7 estuaries simultaneously. In order to have the suitable comparison results, it is necessary to compare by the same lengths of the calculated river sections.

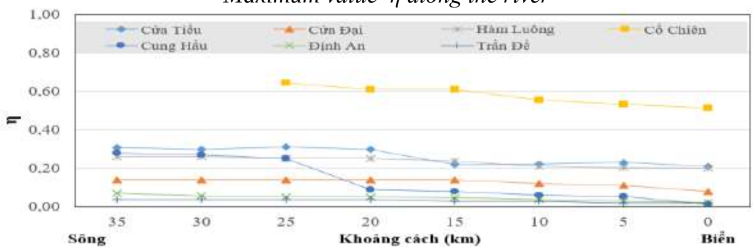
Table 3-1: Integrate and comparison of coefficients η on estuaries of the Mekong River

No	River names		Value	Distance from the sea (km)							
				35	30	25	20	15	10	5	0
				Coefficient η							
1	Tien River	Tieu estuary	Max	4,84	4,69	4,54	4,34	3,88	3,66	3,21	3,04
			Min	0,31	0,30	0,31	0,30	0,22	0,22	0,23	0,21
2		Dai estuary	Max	4,21	4,01	3,84	3,77	3,62	3,46	3,44	3,43
			Min	0,14	0,14	0,14	0,14	0,14	0,12	0,11	0,08
3		Ham Luong	Max	2,67	2,58	2,40	2,34	2,29	2,15	2,12	2,11
			Min	0,26	0,26	0,25	0,25	0,24	0,21	0,21	0,20
4		Co Chien	Max			4,78	4,77	4,77	4,48	4,44	4,43
			Min			0,65	0,61	0,61	0,56	0,53	0,51
5		Cung	Max	2,74	2,74	2,71	2,69	2,68	2,68	2,66	2,55

		Hau	Min	0,28	0,27	0,25	0,09	0,08	0,06	0,05	0,01
1	Hau River	Dinh An	Max	3,08	2,78	2,71	2,68	2,64	2,63	2,42	2,30
			Min	0,07	0,06	0,05	0,05	0,05	0,04	0,03	0,02
2		Tran De	Max	2,59	2,44	2,34	2,32	2,28	2,24	2,20	2,18
			Min	0,04	0,04	0,04	0,04	0,03	0,03	0,02	0,02



Maximum value η along the river



Minimum value η along the river

Figure 3-9: Comparison of η Max and Min values on Mekong river estuaries

On the system of Mekong estuaries, Co Chien branch has the largest coefficient η in both Max and Min values. The maximum value of η is Co Chien, Cua Tieu, Cua Dai, Cung Hau, Dinh An, Ham Luong and Tran De rivers, respectively. The minimum value of η is not similar to the maximum value, but there is a certain change in Co Chien, Cua Tieu, Ham Luong, Cung Hau, Cua Dai, Dinh An, and Tran De respectively. In terms of general trend, Tien river estuaries have higher stratification ability than Hau river ones.

2.3.2. Calculation of stratification by parameter n

On the basis of salinity monitoring data according to the flow depth at the time of March-April 2016 along two branches of Hau river (Tran De branch and Dinh An branch) during high tide and low tide period to calculate the coefficient n to assess the salinity stratification.

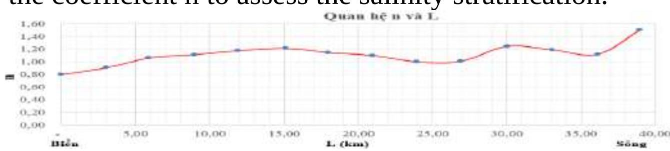


Figure 3-10: Relationship of n and L of Dinh An branch on March 31 (when HWS)

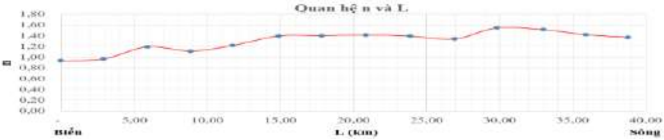


Figure 3-11: Relationship of n and L of Dinh An branch on April 1 (when HWS)

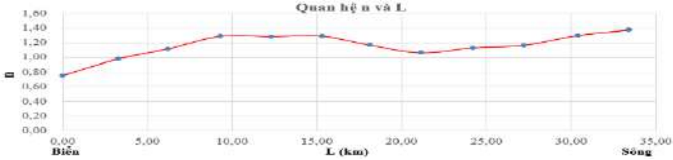


Figure 3-12: Relationship of n and L of Dinh An branch on March 31 (when LWS)

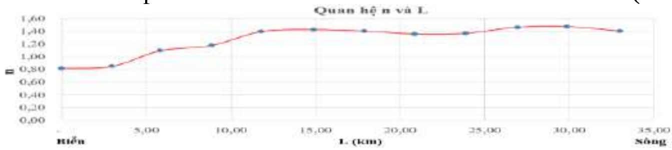


Figure 3-13: Relationship of n and L of Dinh An branch on April 1 (when LWS)

The Dinh An branch of the Hau river appears the stratification in both high and low tide cases. Preliminary calculation results show that the stratification tends to increase gradually from the estuary to the upstream, in the estuary area 3-4 km far from the sea, the stratification is medium and from 4-40 km, the stratification is quite strong.

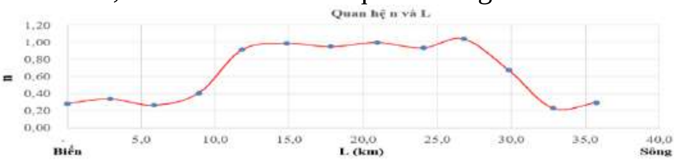


Figure 3-14: Relationship of n and L of Tran De branch on March 31 (when HWS)

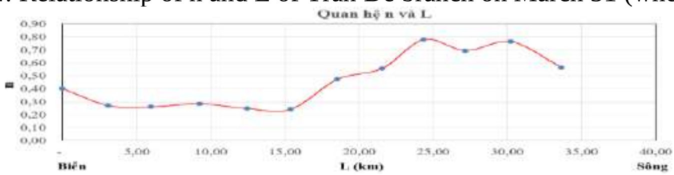


Figure 3-15: Relationship of n and L of Tran De branch on April 1 (when HWS)

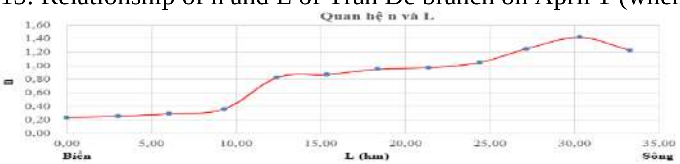


Figure 3-16: Relationship of n and L of Tran De branch on March 31 (when LWS)

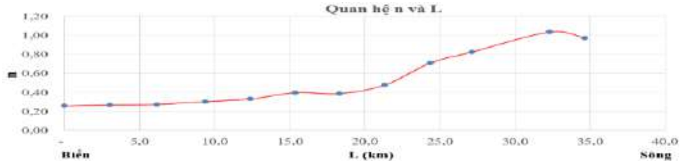


Figure 3-17: Relationship of n and L of Tran De branch on April 1 (when LWS)

At high tide, the average stratification in the high tidal cycle can occur over the entire length of saline intrusion that is surveyed (about 35km far from the sea), although there is location having strong stratification phenomenon, but considering along the entire length, the ability to form salt wedges is very weak. During low tide in Hau river - Tran De branch, stratification occurs from medium to strong one. The average stratification range from the sea to the river is about 20-27km and the strong stratification (salt wedge) is about between 27-40km.

2.3.3. To determine suitable criteria for Mekong river

Based on the results of the stratification mechanism analysis at two Hau river estuaries (Dinh An and Tran De) through parameters n and η, the results are quite similar in terms of space and stratification characteristics (strong, weak stratification and not stratified) it can be seen that the parameter η can be used to preliminarily determine the stratification characteristics and classification of estuaries quite well. The determination of parameter η is quite simple and easy to implement based on simple calculation results from one-dimensional hydraulic models or observed values of river discharge. In the current conditions when the monitoring and measurement of salinity is limited, the parameter η is a suitable choice to determine the stratification mechanism for the estuary.

Through the calculation results of the estuary coefficients to evaluate and determine the level of stratification, the calculation results only reflect the ability of stratification. However, a question arises if stratification, how much is the salinity concentration, density, etc. of the aquifers according to the depth and how different it is, then the calculation results cannot be answered, so the practical application is not high.

2.4. Numerical model in saline intrusion research

To study the mechanism of saline stratification will definitely have to use 2 D model by vertical direction x - z or 3D model. Currently, there are many models that can be applied in computational research, but based on the required conditions that Ph D student can meet such as data, documents, user experience, computer equipment and license to use; in the thesis, Ph student has applied the modules in the MIKE software set MIKE3 to evaluate and clarify in more detail the stratification phenomenon, to describe the structure of the salt wedge in the estuary.

CHƯƠNG 3. CHAPTER 3. RESEARCH RESULTS AND DISCUSSION ON SALINE INTRUSION MECHANISM IN HAU RIVER ESTUARY

3.1. To set up a computational research model

The calculation diagram is st up from Can Tho to the East Sea to ensure the accuracy and stability of the model at the sea level boundary, which will be taken out to sea from the shore about 50km.

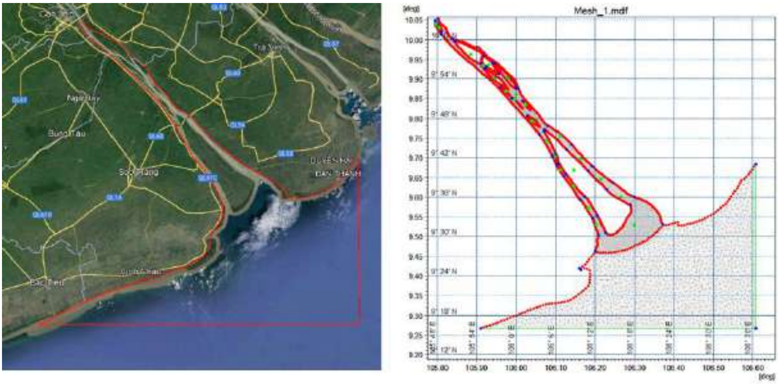


Figure 3-18: P Calculation scope for the study area

To calculate for the scenarios the model has been calibrated and verified to determine the set of calculated model parameters.

3.2. Representative calculation results

3.2.1. Calculation results along two branches of the Hau river

Through the calculation results for the time of the three tides in the low, medium and high tide periods in the dry season, some general comments can be drawn about the stratification of salinity and wedge as follows:

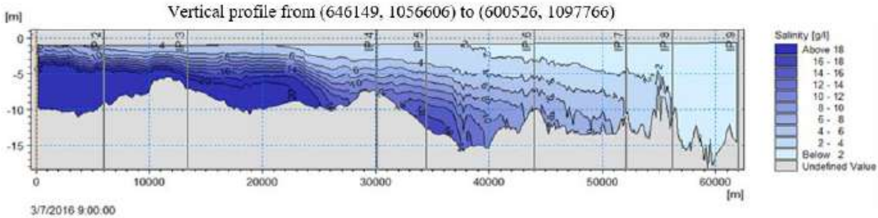
- In terms of shape, the salt wedge always tends to be thin during low peak tide and low tide and gradually increases during high tide and peak tide. The change of salt wedge shape mainly takes place during two periods of high tide and low tide of the low-tide branch, and in the period between the two high peak tide and low peak tide, the salt wedge has less changed.
- The development speed of the salt wedge is not equal between the surface and the bottom layer, the speed of the upper layer is faster than the bottom layer, which is the cause of the change in the shape of the salt wedge. The seaward movement of the salt wedge at low tide is faster than at high tide.
- The comparison of salt wedges between Dinh An and Tran De river branches shows that Dinh An branch tends to be thinner and more flat than Tran De branch at all times of the tidal periods. In the Dinh An branch, the shape of the salte wedge changes over time faster than

that of the Tran De branch, and the length of the Dinh An branch saline wedge also penetrates further than that of the Tran De branch, up to a maximum of 10km.

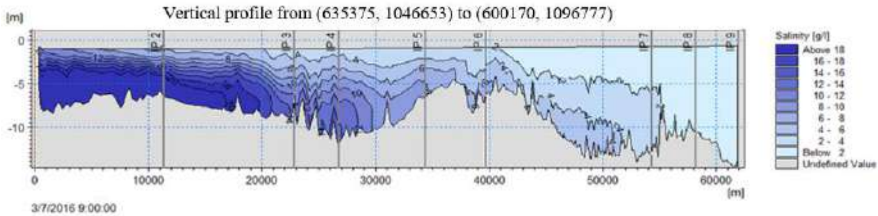
Table 3-2: Some summary results on longitudinal river salinity stratification

River name	Time to extract results	Salt wedge shape	Length of salt wedge (km)		Distance with the beginning of Dung Island (km)	
			Surface	Bottom	Surface	Bottom
I	**Low tide period**					
Dinh An	5h 4/3/2016 - Tidal low peak	Flat	11,0	26,0	26,0	11,0
Tran De		Sloping	20,5	24,0	18,4	14,9
Dinh An	13h 4/3/2016 - tide peak	Flat	22,5	31,5	14,5	5,5
Tran De		Sloping	24,5	28,5	14,4	10,4
Dinh An	17h 4/3/2016 - Tidal low peak	Flat	26,5	36,5	10,5	0,5
Tran De		Sloping	30,5	32,0	8,4	6,9
Dinh An	22h 4/3/2016- tide peak	Flat	30,5	39,0	6,5	-2,0
Tran De		Sloping	32,5	33,5	6,4	5,4
Dinh An	06h 5/3/2016 - Tidal low peak	Flat	9,0	33,0	28,0	4,0
Tran De		Sloping	17,5	26,0	21,4	12,9
II	**Mean tide period**					
Dinh An	9h 7/3/2016 - Tidal low peak	Flat	19,0	46,0	18,0	-9,0
Tran De		Flat	19,5	39,0	19,4	-0,1
Dinh An	15h 7/3/2016 – tide peak	Flat	29,0	44,0	8,0	-7,0
Tran De		Sloping	29,5	36,0	9,4	2,9
Dinh An	20h 7/3/2016 - Tidal low peak	Flat	40,5	48,5	-3,5	-11,5
Tran De		Sloping	37,0	37,5	1,9	1,4
Dinh An	02h 8/3/2016 - tide peak	Flat	29,0	44,0	8,0	-7,0
Tran De		Sloping	34,5	45,5	4,4	-6,6
Dinh An	10h 5/3/2016 - Tidal low peak	Flat	19,0	47,5	18,0	-10,5
Tran De		Flat	27,5	41,5	11,4	-2,6
III	**High tide period**					
Dinh An	12h 10/3/2016 - Tidal low peak	Flat	21,0	41,5	16,0	-4,5
Tran De		Sloping	27,0	31,5	11,9	7,4
Dinh An	17h 10/3/2016 - tide peak	Fairly flat	31,5	40,5	5,5	-3,5
Tran De		Sloping	34,0	34,0	4,9	4,9
Dinh An	0h 10/3/2016 - Tidal low peak	Fairly flat	30,0	40,5	7,0	-3,5
Tran De		Sloping	32,5	34,0	6,4	4,9
Dinh An	5h 11/3/2016 - tide peak	Fairly flat	35,0	41,0	2,0	-4,0
Tran De		Very sloping	33,5	33,5	5,4	5,4
Dinh An	12h 11/3/2016 – Tidal low peak	Fairly flat	21,0	31,5	16,0	5,5
Tran De		Sloping	24,5	29,5	14,4	9,4

Figures of some results of salinity distribution along two branches of Hau river

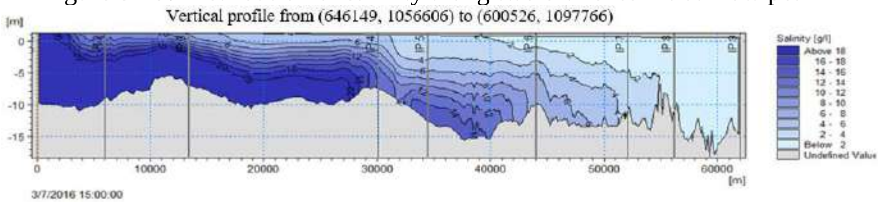


Dinh An branch

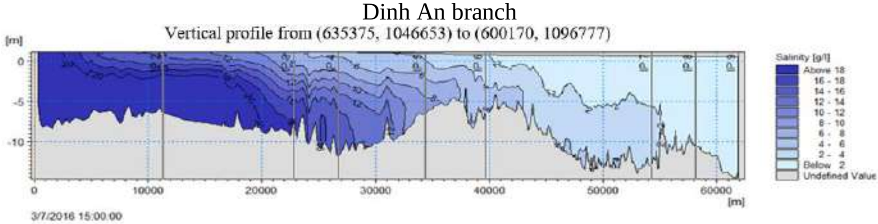


Tran De branch

Figure 3-19: Distribution of salinity along two branches - tidal low peak



Dinh An branch



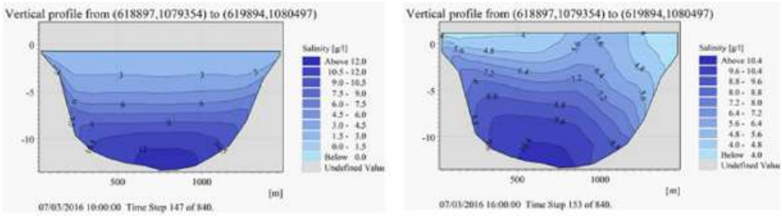
Tran De branch

Figure 3-20: Distribution of salinity along two branches - tidal peak

3.2.2. Calculation results on representative cross-section

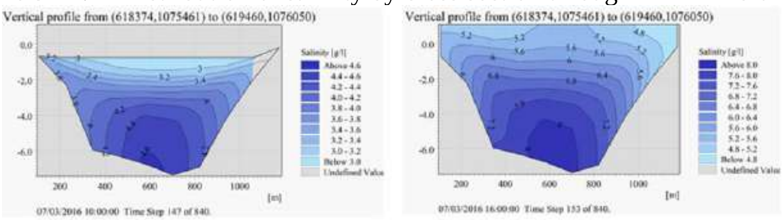
During the low and medium tide period, the upper water layer (about 40-50% of the depth) the salinity concentration close to the shore tends to be higher than in the middle of the river and the isosalinity tends to curve according to the cross-sectional shape, curved top is towards the bottom, in contrast to the deep (50%) lower layers, the trend is inversely that the salinity concentration in the shore tends to be smaller in the middle of the river, and the isosalinity has a curved top that is upwards to the free surface.

From the analysis results on the cross section, stratification on the cross section is also similar to the river longitudinal axis. During low tide and medium tide period, the salinity stratification on the cross-section is stronger than during high tide period and in a tidal period, the time of low peak tide has stratificated more clearly than the period of peak tide. During low tide and low peak tide, the river flows out in combination with the falling tide, so in the middle of the river (thalweg) the salinity concentration will be lower than the two banks and vice versa during high tide, the tide flow has flowed inversely towards the river side through the thalwegs, so the salinity concentration in the middle of the river is higher than the two banks.



Low tide Peak tide

Figure 3-21: P Distribution of salinity by cross section through Dinh An branch



Low tide Peak tide

Figure 3-22: Distribution of salinity by cross section through Tran De branch

3.2.3. Calculation results on the layout according to the depth layers

The gures of the salinity distribution on the layout according to the depth layers are quite different. The seperation trend on the strata has a clear difference between the top and bottom layers and at many times, the trend is opposite in the tidal times of the day. At the time of low peak tide and ebb tide, the salinity distribution tends to be distributed to the two shores and forms isosalinity lines with a curved direction towards the sea and a sharper shape in the deep layer, the bottom layers have opposite tendency, the salinity on two banks are lower and the curve of the isosalinity is towards the river side.

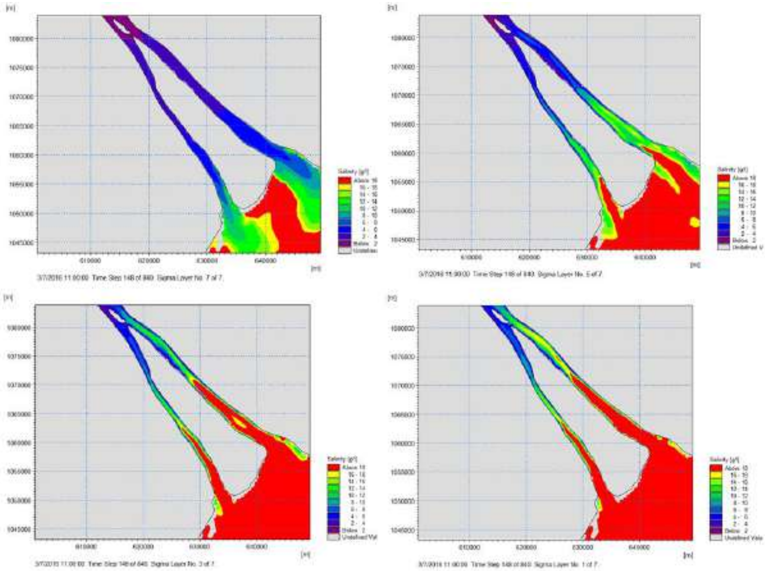


Figure 3-23: Distribution according to depth layers

3.3. Calculation results in case of sea level rise

Calculation results also show that sea level rise will push the salt wedge further into the river, the additional distance depends on tide times of the day, different tide periods in the tidal cycle, trend, speed of salt wedge development are different between the upper and lower layers and the maximum increase distance is about 7-8km for the bottom layer and about 2-4km for the surface layer.

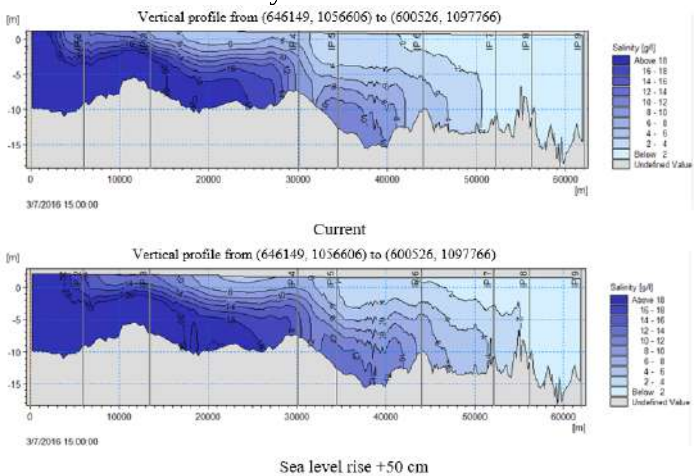
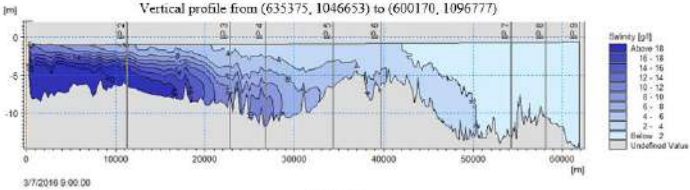
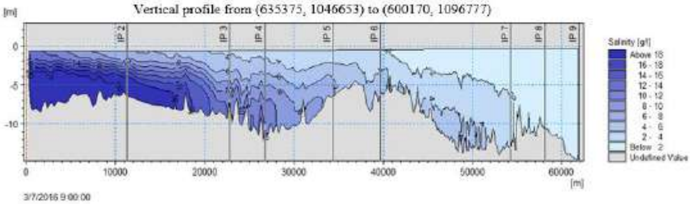


Figure 3-24: Comparison of salinity distribution in Dinh An branch



Current



Sea level rise +50 cm

Figure 3-25: Comparison of salinity distribution in Tran De branch

CHƯƠNG 4. CHAPTER 4. ORIENTATION OF THE BASIC PROPOSED SOLUTIONS FOR REASONABLE WATER EXPLOITATION FOR THE COASTAL RIVER OF THE MEKONG DELTA

4.1. To select the ability to take water according to space and time

To select the time to get water: Given the current production status of the Mekong Delta's coastal areas is agriculture and aquaculture growing, then the ultimate aim of the study of salinity forecast will be the ability to obtain fresh water or have different suitable salinities for aquaculture growing... at different times (periods, times) during the dry season, during the tidal cycle, during the day, even every hour of the day.

Water intake ability based on longitudinal direction and depth: The calculation results using the 3D model will calculate the increase in the length of fresh water intake along the river (during low tide) if using the 3D model, the increased range water with salinity concentration <4g/l (fresh water obtaining) with a length downstream of about 15km with the upper layers of water with a depth from the water surface down to about 0-5.0m.

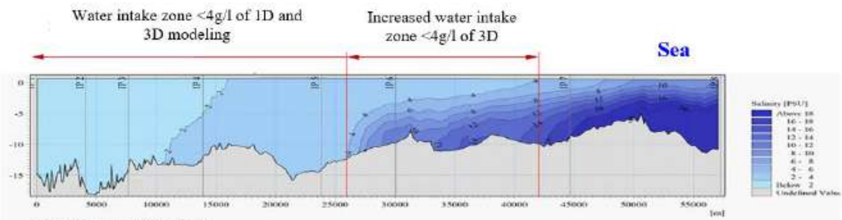


Figure 4-1: Illustration of the range of water intake with salinity <4g/l

Selection of locations to collect water on the layout: With the distribution of salinity when calculated by 3D models on the layout of different depth layers, so it is possible to obtain water with different salinity concentrations at locations on the layout. The ability to collect water on the cross-section: to select the location to collect water with the above-required salinity concentration in the horizontal and deep cross-section will more fully supplement the exploitation of research results into practice.

4.2. Application in the work design and operation

+ *Application to design, upgrade and operate saline control sluices*

To design saline control sluice with suitable bottom elevation according to actual requirements of water supply so that water with suitable salinity can be obtained.

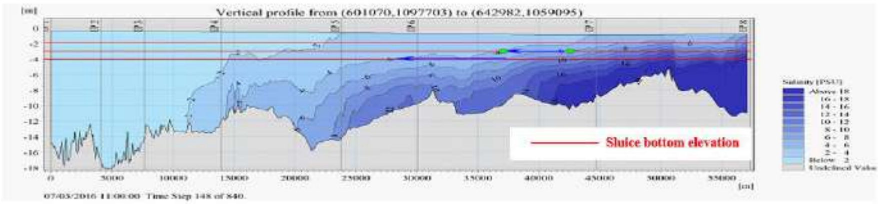


Figure 4-2: Illustration of salinity stratification and arrangement of bottom elevations of water collection

In order to collect water according to the depth of the valve gate, it can be designed into several steps, valve gate is in another valve gate (the small gate is in the large valve gate) so that it can be operated to forcely change the water intake level or take fresh water.

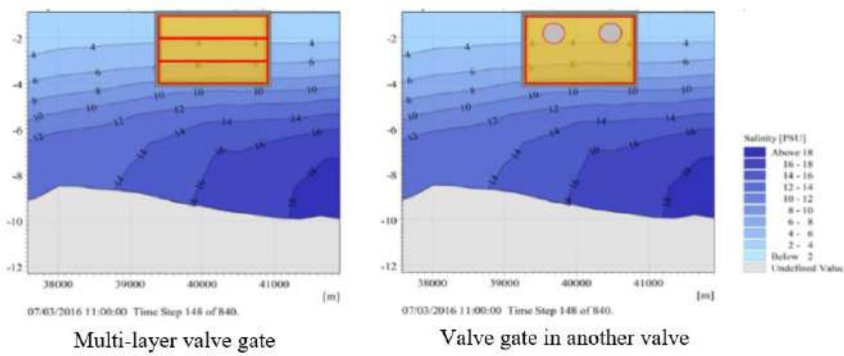


Figure 4-3: Illustration of a multi-layer valve gate and valve gate in another valve gate

+ *Application to the design of pumping stations to take water for production*

In order to obtain water with the appropriate required salinity, the mobile floating pumping station solution is a smart, feasible and suitable choice, especially for the area with a favorable river system in the Mekong Delta. Based on the actual salinity monitoring results in the field and especially the forecast results from the 3D model, it will determine the salinity concentration at each time, each location according to space, will develop an operation plan. movement of pumping stations to get water with suitable salinity.

CONCLUSION AND RECOMMENDATION

Conclusion

The thesis has maken scientific and practical contributions to the research on saline intrusion in estuaries and has the following new contributions:

1. Some empirical parameters can be used to preliminarily evaluate the stratification phenomenon for the 7 branches of the Mekong River in space (along the river) and in time.
2. Set up a 3 D model (MIKE 3) and simulate the characteristics of saline intrusion, saline distribution, structure (shape, size, slope), formation, existence and development of salt wedge at two branches of Hau river.
3. Based on the results of the simulation of saline intrusion, the saline stratification, it has oriented the basis for proposing a reasonable water development solution for the coastal estuaries of the Mekong Delta (design ideas, upgrading, direction of adjustment the way how to operate the works according to the requirements of salinity concentration in accordance with different production requirements in the estuary of the Mekong Delta).

Recommendations

1. The research problems of the PhD student are quite intensive and have not been paid much attention in Vietnam in general and the Mekong Delta in particular, then the sources of data and experience in the research are still limited, so there are still some unresolved issues. Some remaining limitations can be listed as: fully calculating the factors affecting the stratification mechanism, salt wedge such as changes in upstream flow, subsidence of the riverbed, changes in production upstream and within the Mekong Delta. Further research is needed for the solutions of large sluice gates, underground dams or artificial islands in the estuary to control saline intrusion on the built 3D model.

2. In order to study the calculation with high accuracy, it is necessary to conduct more surveys on hydraulics, saline intrusion on a large scale and monitor the spatial dimensions of the flow at different times of the year.

LIST OF PUBLISHED WORKS RELATED TO THE THESIS

1. **Do Dac Hai** (2020), “Evaluation of the characteristics of salinity stratification in the Hau river estuary through observed data and experimental formulas”, *Journal of Water Resources Science and Technology, Vietnam Academy for Water Resources (ISSN: 1859-4255)*, No. 59 (April 2020), pages 34-45.
2. **Do Dac Hai** (2020), “Using a 3-D mathematical model to simulate saltwater propagation in the Hau River estuary”, *Journal of Water Resources Science and Technology, Vietnam Academy for Water Resources (ISSN:1859-4255)*, No 61 (August 2020), pages 66-79.
3. Nguyen An Nien, Nguyen Cong Anh, **Do Dac Hai** (2021), “To propose to supply fresh water to the coastal area of the Mekong Delta in the dry season in a sustainable”, *Journal of Water Resources Science and Technology, Vietnam Academy for Water Resources (ISSN:1859-4255)*, No 64 (February 2021), pages 2-7.
4. **Do Dac Hai** (2018), “Assessing the impact of urbanization, construction of flood control works on saline intrusion in the downstream area of Dong Nai - Sai Gon river”, *Journal of Water Resources Science and Technology, Vietnam Academy for Water Resources (ISSN:1859-4255)*, No 49 (November 2018), pages 27-35.
5. Pham The Vinh, **Do Dac Hai**, Nguyen An Nien (2016), “Try to find the speed of tidal propagation in the river system”, *Collection of works, Vietnam Association of Hydraulic Mechanics*, 19th edition (July 28-30, 2016), pp. 445-452
6. Tran Dinh So, Nguyen Phu Quynh, **Do Dac Hai** (2011), “Solutions to renovate and upgrade valve gates and equipment for salinity control works in the Mekong Delta to adapt to climate change”, *Journal of Water Resources Science and Technology, Vietnam Academy for Water Resources (ISSN:1859-4255)*, No 04 (October 2011), pages 41-45.
7. **Do Dac Hai**, Huynh Thanh Son (2005), “Calculation of saline intrusion on the Saigon River under the impact of Dau Tieng reservoir”, *Journal of Water Resources Science and Technology, Vietnam Academy for Water Resources (ISSN:0866-7292)*, pages 193-198.

----------------------///----------------------